High Temperature Materials

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Classification of High Temperature Materials

- Broad Categories of High Temperature Materials
  - Metallics
  - Intermetallics
  - Ceramics/Refractories

Classification of High Temperature Materials (Continued)

- Metallics are Classified in Many Ways
  - Based on major alloying elements
    - Iron base
    - Nickel base
    - Cobalt base
    - Refractory metals (Mo,W, ect.)
  - Based on major scale formation on surface at high temperature in air
    - Chromia formers
    - Aluminum formers
    - Silica formers
  - Based on processing method
    - Polycrystalline
      - Cast
        - Static
        - Investment
        - Centrifugal
        - Directionally solidified
        - Single crystal
      - Wrought
        - Forged
        - Extruded
        - Rolled
      - Powder metallurgy
        - Oxide dispersion strengthened (ODS)

Classification of High Temperature Materials (Continued)

- Intermetallics are Ordered Structures and are Classified Based on Major Alloying Elements
  - Aluminides
    - Ni_3Al
    - NiAl
    - Fe_3Al
    - FeAl
    - Ti_3Al
    - TiAl
  - Silicides
    - Ni_3Si

Classification of High Temperature Materials (Continued)

- Ceramics and Refractories are Classified Based on Major Compound-Forming Element
  - Oxides
    - SiO_2
    - Al_2O_3
    - ZrO2
    - Cr_2O_3
  - Nitrides
    - Si_3N_4

General Properties of Interest for High Temperature Metallic and Intermetallic Materials Include

- **Melting Point**
  - **This limits the upper use temperature.**
- **Creep Strength**
  - **This is the primary deformation mode at high temperatures for steady state loading.**
- **Fatigue and Thermal Fatigue Resistance**
  - **Needed for cyclic (mechanical and thermal) loading**

General Properties of Interest for High Temperature Metallic and Intermetallic Materials Include (Continued)

- Environmental Resistance
  - Needed for specific applications
    - Oxidation
    - Carburization
    - Sulfidation
    - Molten salts
    - Liquid metals
  - Ease of processing
  - Ease of Fabrication and field repair
  - Cost

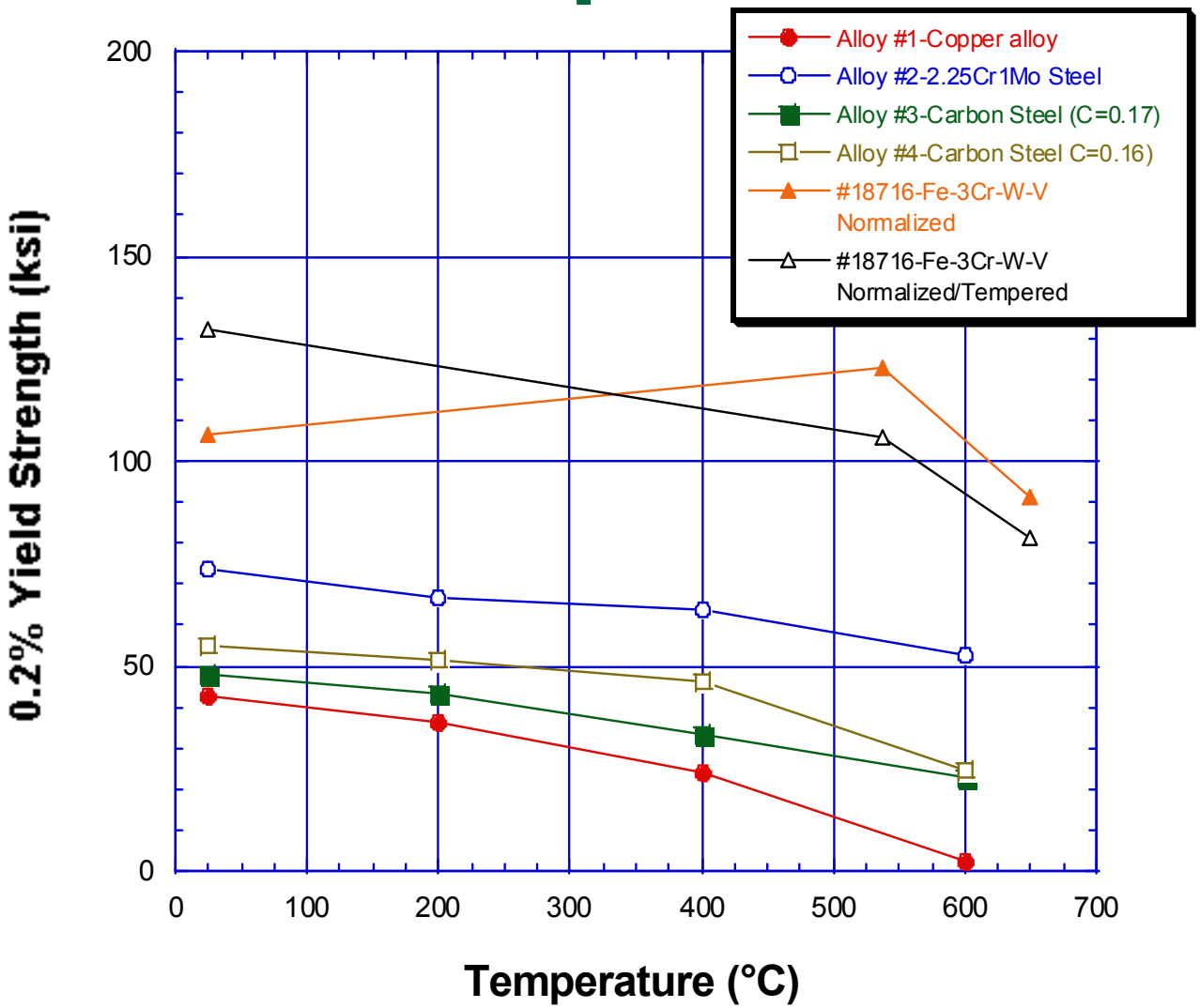
Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL

- **Ferritic Steels**
  - Grade 91 was developed in 1978-1982 (commercialized)
    - It is a Fe-9Cr-1Mo alloy with strengthening from controlled additions of Nb and V
    - ASME Code approved
    - Commercially produced and used in many countries of the world
    - Major applications include
      - Main steam piping
      - Reheater and superheater tubes
      - Headers
      - Pressure vessels
    - Sales
      - Several hundred million dollars

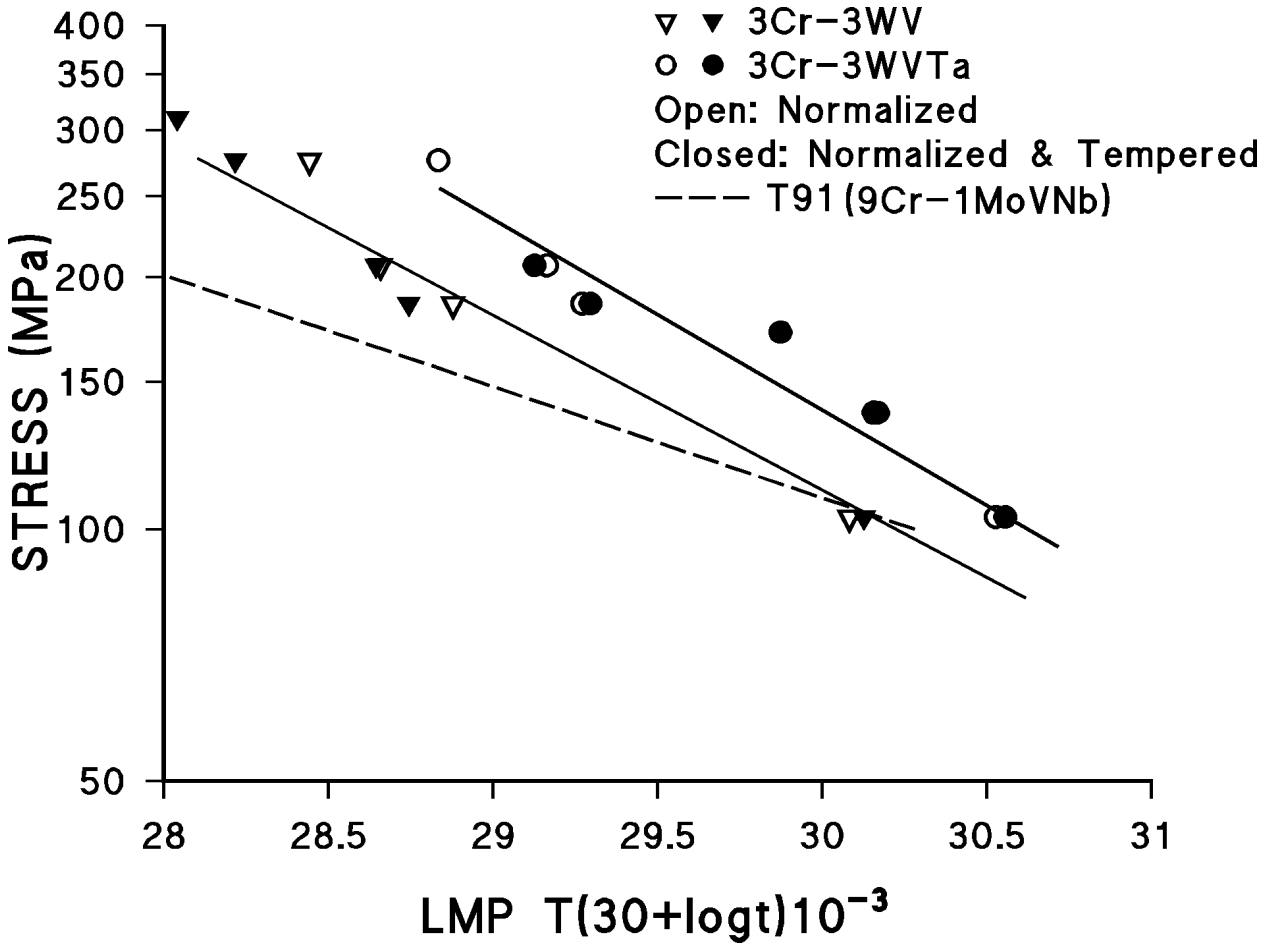
Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

- **Ferritic Steels (Continued)**
  - **Grade 33 (currently under development)**
    - **It is a Fe-3Cr-3W(V) alloy.**
    - **It has the combination of high temperature strength and low temperature toughness.**
    - **Primary benefit of this alloy is the strong potential for NOT REQUIRING POSTWELD HEAT TREATMENT.**
    - **Major applications include**
      - **Chemical reactor vessels**
      - **Headers**
      - **Steam drums**
      - **Waterwall boilers**
      - **Reheater tubes for heat recovery systems**
    - **Nooter to commercialize the alloy.**

0.2% Yield Strength as a Function of Temperature

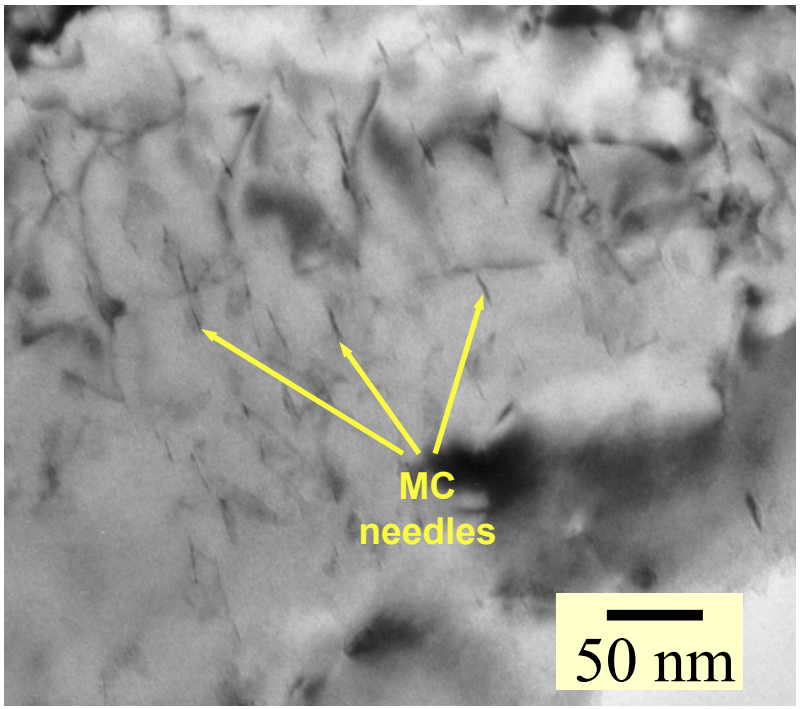


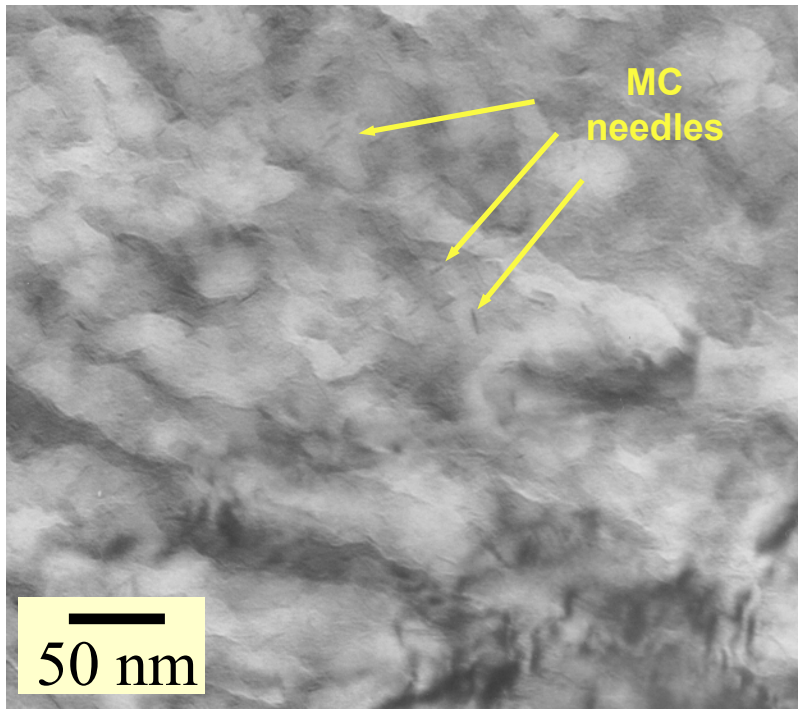
Creep Rupture Strength of 33VT Alloy is Nearly a Factor of 2 Higher than T23 and the High-Strength Grade T91 of Fe-0Cr-1Mo Steel



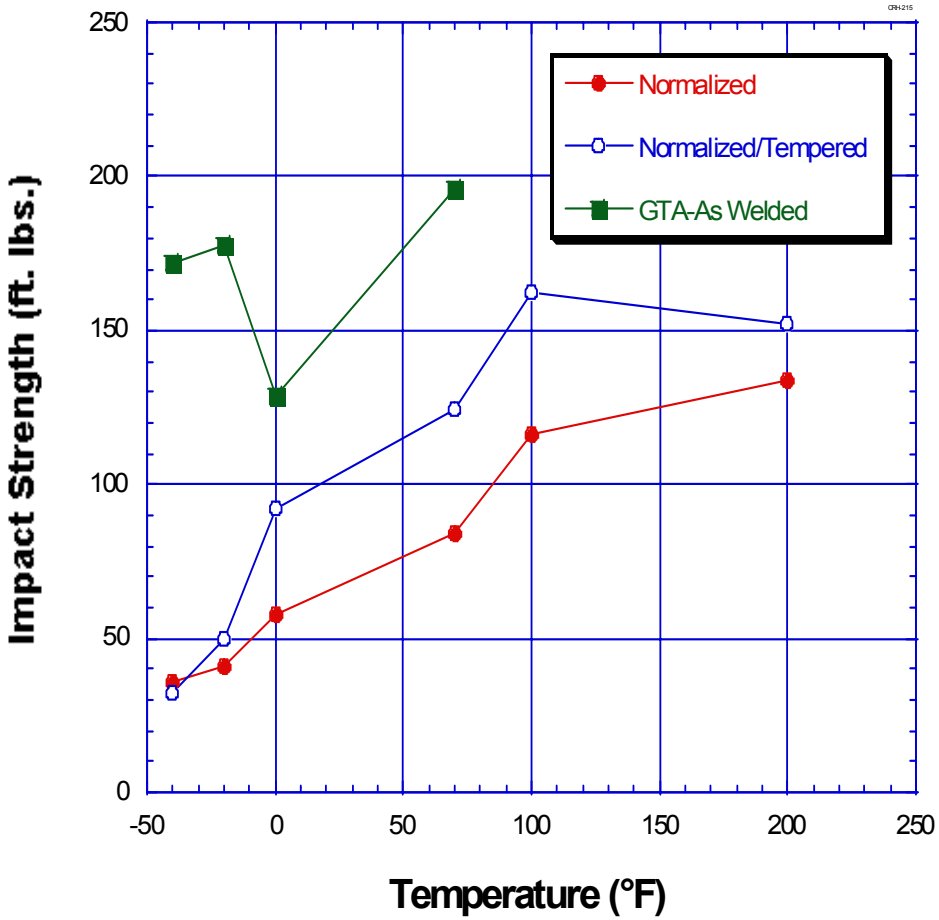
Dispersion of Nano-size V-rich MC Needles in Both 3Cr-3WV and 3Cr-3WVTa Alloys are the Likely Mechanism for Their High Strength

TEM (foil) 3Cr-3WV (N+T) TEM (foil) 3Cr-3WVTa (N+T)





Charpy Impact Properties of GTA Weld in Heat 18687 with its Matching Filler Wire

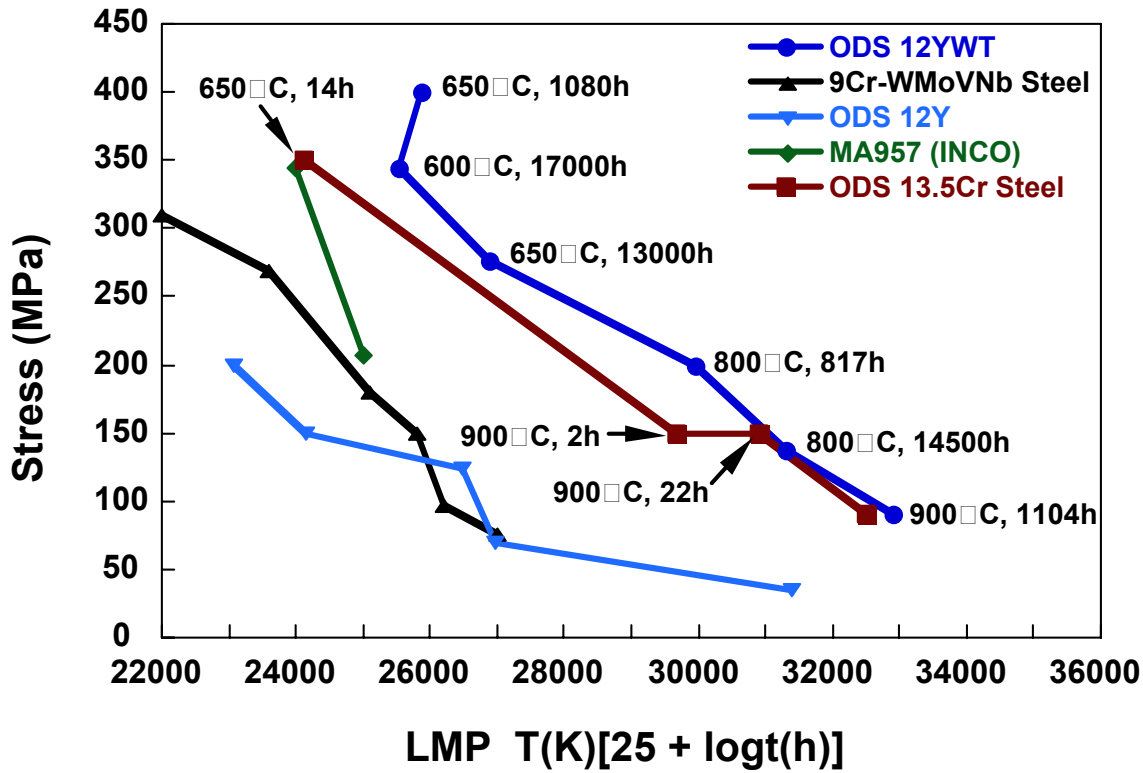


Element	18687	GTA Weld 18687
C	0.07	0.052
Mn	0.2	0.2
P	0.008	0.006
S	0.005	0.005
Si	0.21	0.24
Ni	1.00	1.00
Cr	3.03	3.07
Mo	0.78	0.77
V	0.25	0.25
Cb	0.002	0.003
Ti	0.003	0.003
Co	0.008	0.007
Cu	0.01	0.01
Al	0.004	0.004
B	0.001	0.001
W	1.56	1.54
As	0.001	0.002
Sn	0.002	0.002
Zr	<0.001	<0.001
N	0.001	<0.001
O	0.003	0.002
C (Eq 1)	1.139	1.125

Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

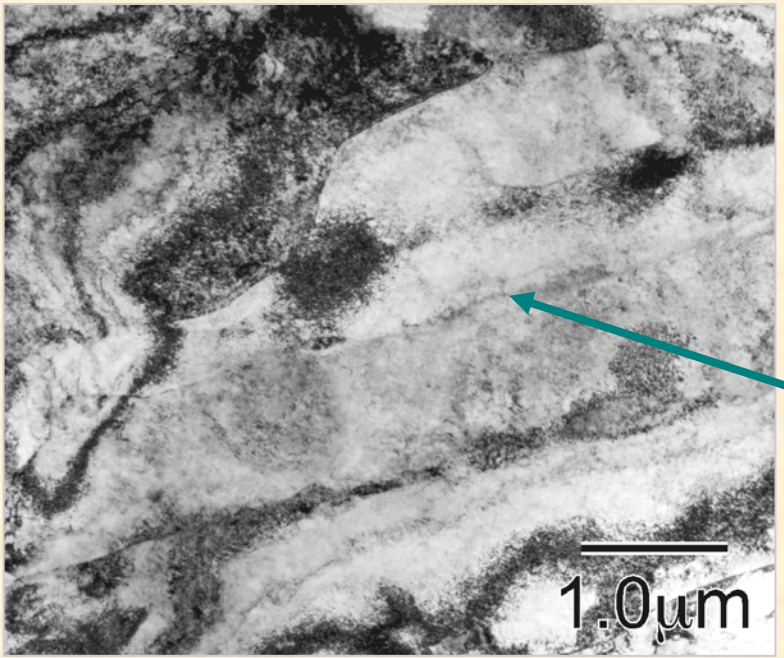
- Ferritic Steels (Continued)
  - Nanophase stabilized ferritic steel (proof-of-concept demonstrated)
    - It is a Fe-12Cr-1Mo alloy stabilized with nanophase particles.
    - It has creep strength that exceeds any of the ferritic steels.
    - Primary benefit of nanophase strengthening makes it suitable for use up to temperatures exceeding 800°C.
    - Major applications include
      - Applications with large mechanical and thermal loading (high thermal fatigue resistance from low thermal expansion and high thermal conductivity and high strength)
    - Need to initiate development project
      - Develop low cost methods for incorporation of nanophase structures
      - Property determination
      - Processing and fabrication methods
      - Pilot scale testing
      - Expand concept to other alloys (austenitics and nickel base)

Long-Term, High Temperature Strength of Dispersion Strengthened Ferritic Alloys

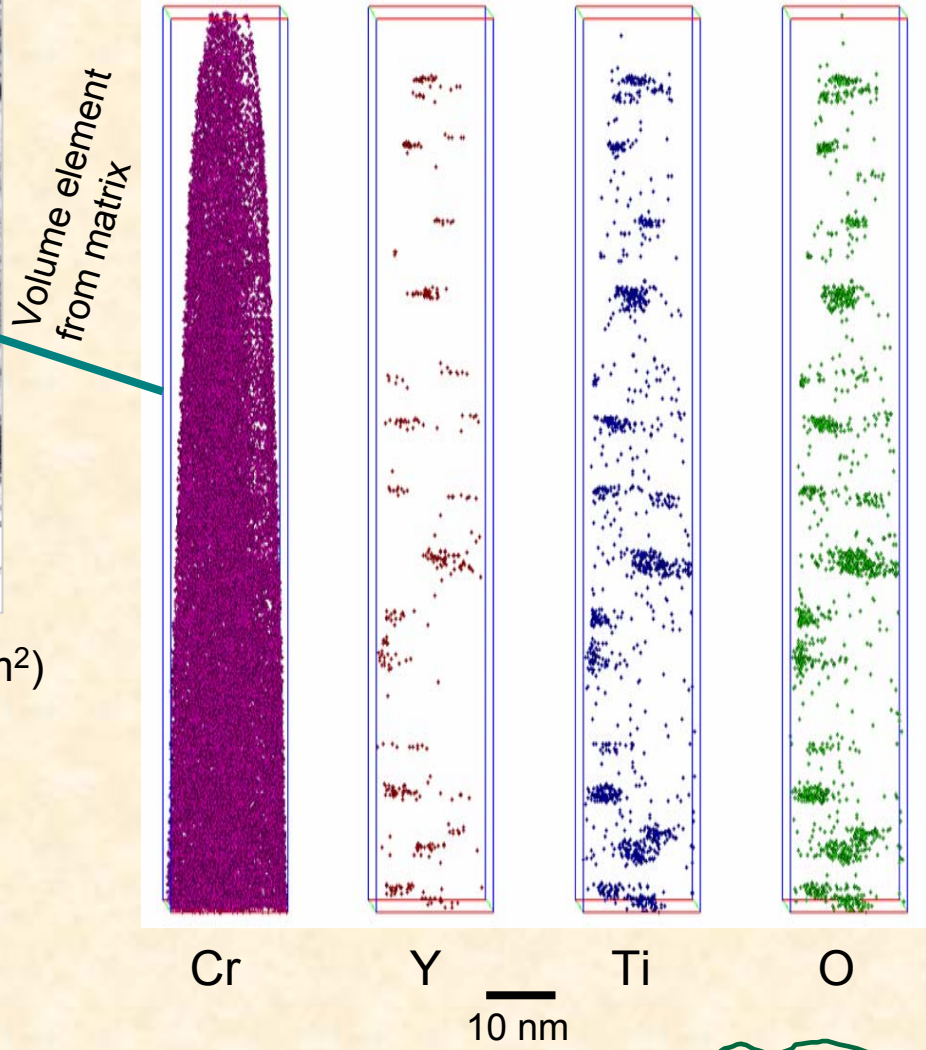


- NCF steel (12YWT)
- Experimentally developed ODS 13.5Cr steel (PNNL, Vista Metal, and U. Idaho)

Microstructure of the As-Processed MA 12YWT Ferritic Alloy

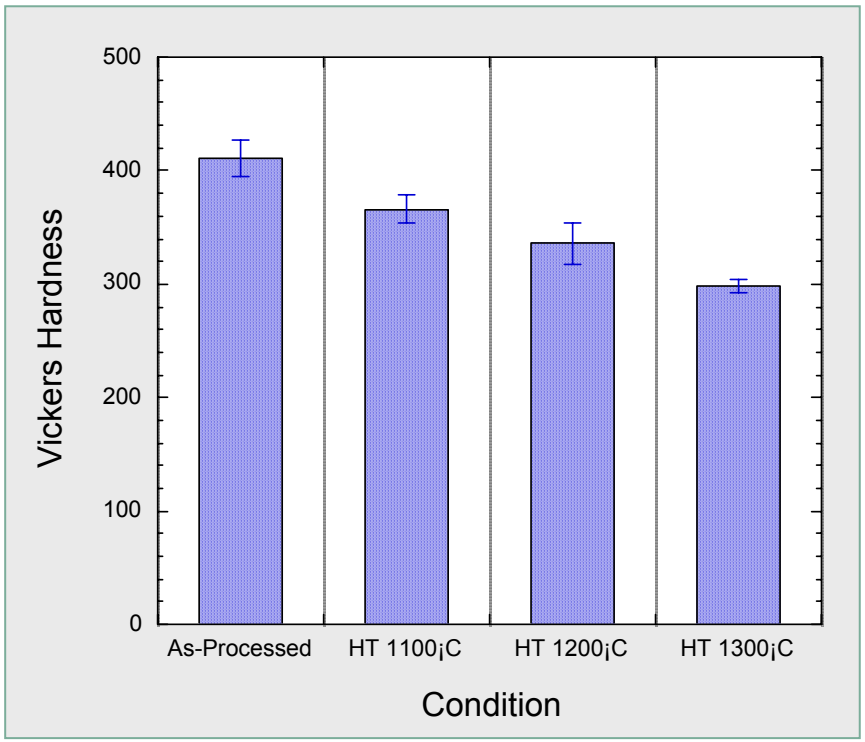


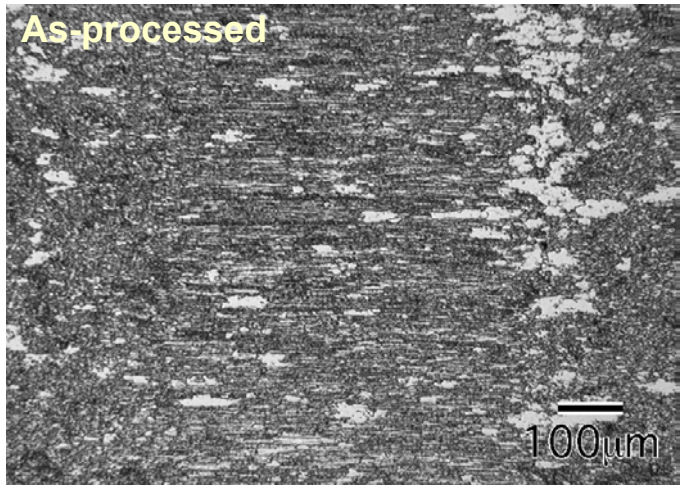
3-D Atom Probe Tomography

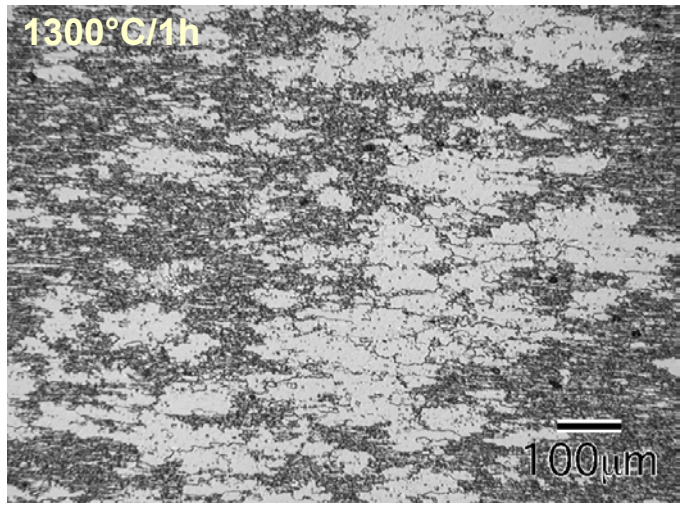


- elongated grains containing high (~$10^{24}/m^2$) dislocation number density
- very high number density of ~$10^{24}/m^3$ of uniformly distributed nanoclusters
  - site occupancy on bcc Fe lattice
  - average size r_g = 2.0 (+/- 0.8) nm

Microstructural Stability Observed in 12YWT Alloy with Short Term Exposure at Very High Temperatures







- Softening is not significant
- ~50% of the microstructure has recrystallized after annealing for 1h at ~86% T_{MP}(~1520°C)

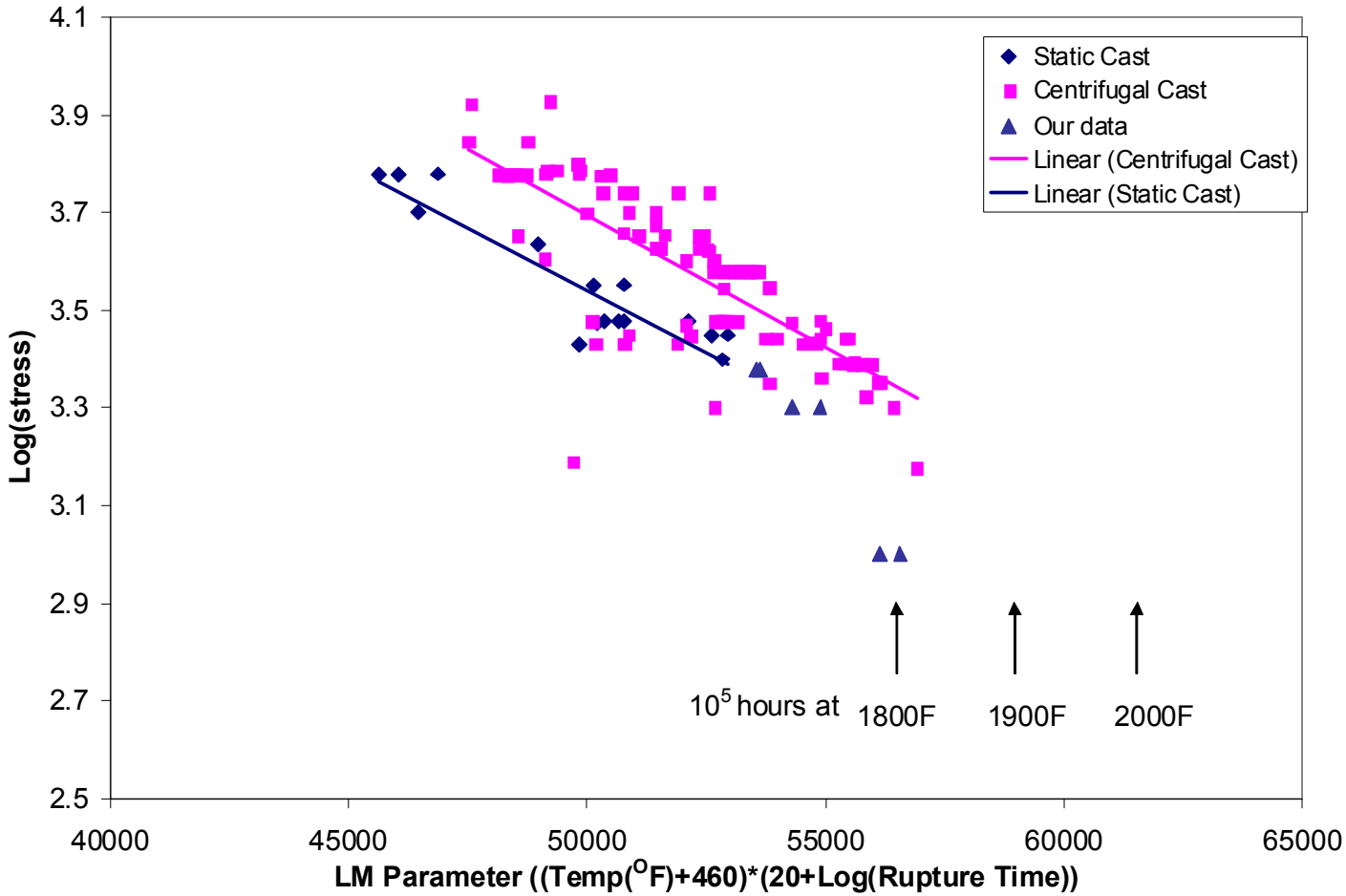
Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

- **Austenitic Steels (Continued)**
  - **H-Series (currently under development)**
    - **These are cast austenitic steels and commonly known as HP, HT, and HK.**
    - **Excellent combination of**
      - **Creep strength**
      - **High temperature resistance to many environments**
    - **Easily castable and weldable**

Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

- Austenitic Steels (Continued)
  - H-Series (Continued)
    - Major applications include
      - Transfer rolls
      - Radiant burner tubes
      - Heat treating fixtures
      - Ethylene cracking tubes
      - Many others
    - Project objectives
      - Improve upper use temperature
      - Develop strength predicting capability based on composition input
    - Duraloy Technologies to commercialize new compositions

Data for H-Series Steels are being Separated Based on Casting Process and Verified by Tests at ORNL



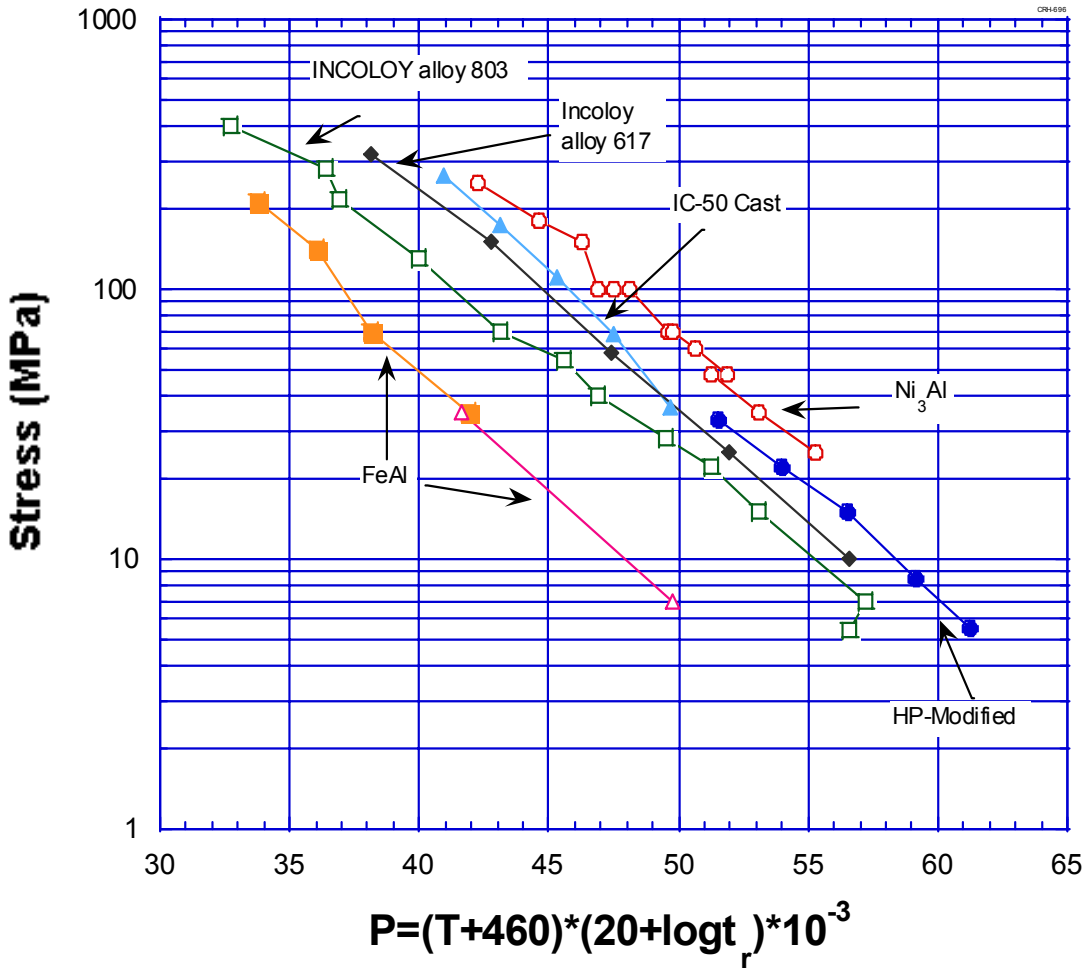
Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

- **Intermetallics**
  - **Ni_3Al-based alloys developed in 1982-2002 (near commercialization)**
    - **Ordered alloys strengthened with controlled addition of Mo and B**
    - **Made castable and weldable by addition of Zr**
    - **Excellent combination of properties**
      - **Tensile and creep strength**
      - **Oxidation resistant**
      - **Carburization resistant**
    - **Exo-Melt™ process developed for its melting**
    - **Castable by static and centrifugal methods**

Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

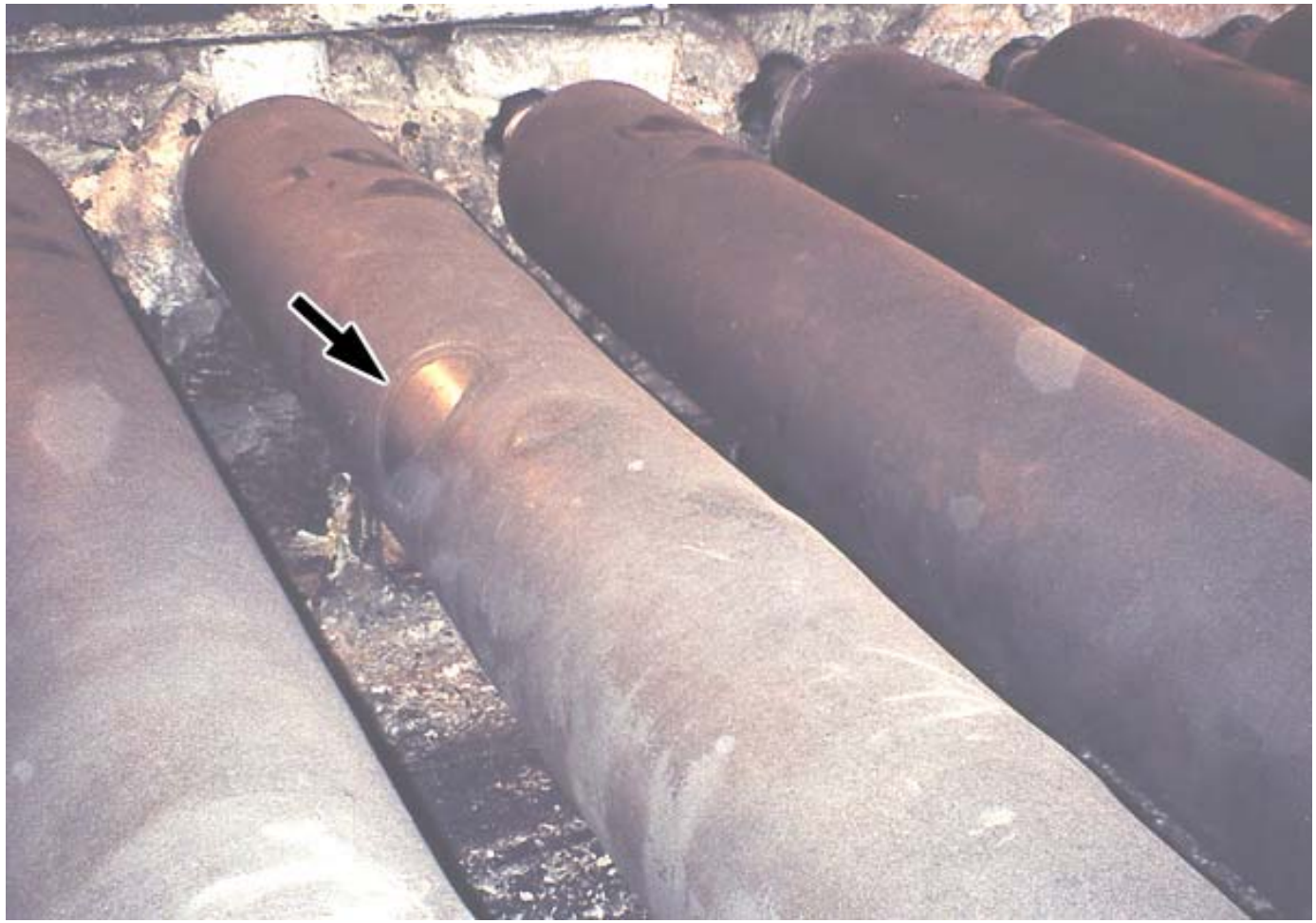
- Intermetallics (Continued)
  - Ni_3Al-based (Continued)
    - Weldable by MIG process
    - Major applications include
      - Transfer rolls for heat treating furnaces (up to 1000°C)
      - Fixtures for carburizing furnaces
      - Radiant burner tubes
      - Annealing rolls (used as coatings)
    - Producers with experience include
      - Duraloy Technologies
      - Alcon Industries
      - Ultracast
      - Alloy Engineering & Casting
      - United Defense
      - Stoody Company
      - Ametek
      - Deloro Stellite

Nickel Aluminide has the Highest Creep Rupture Strength as Compared to Commercial Alloys

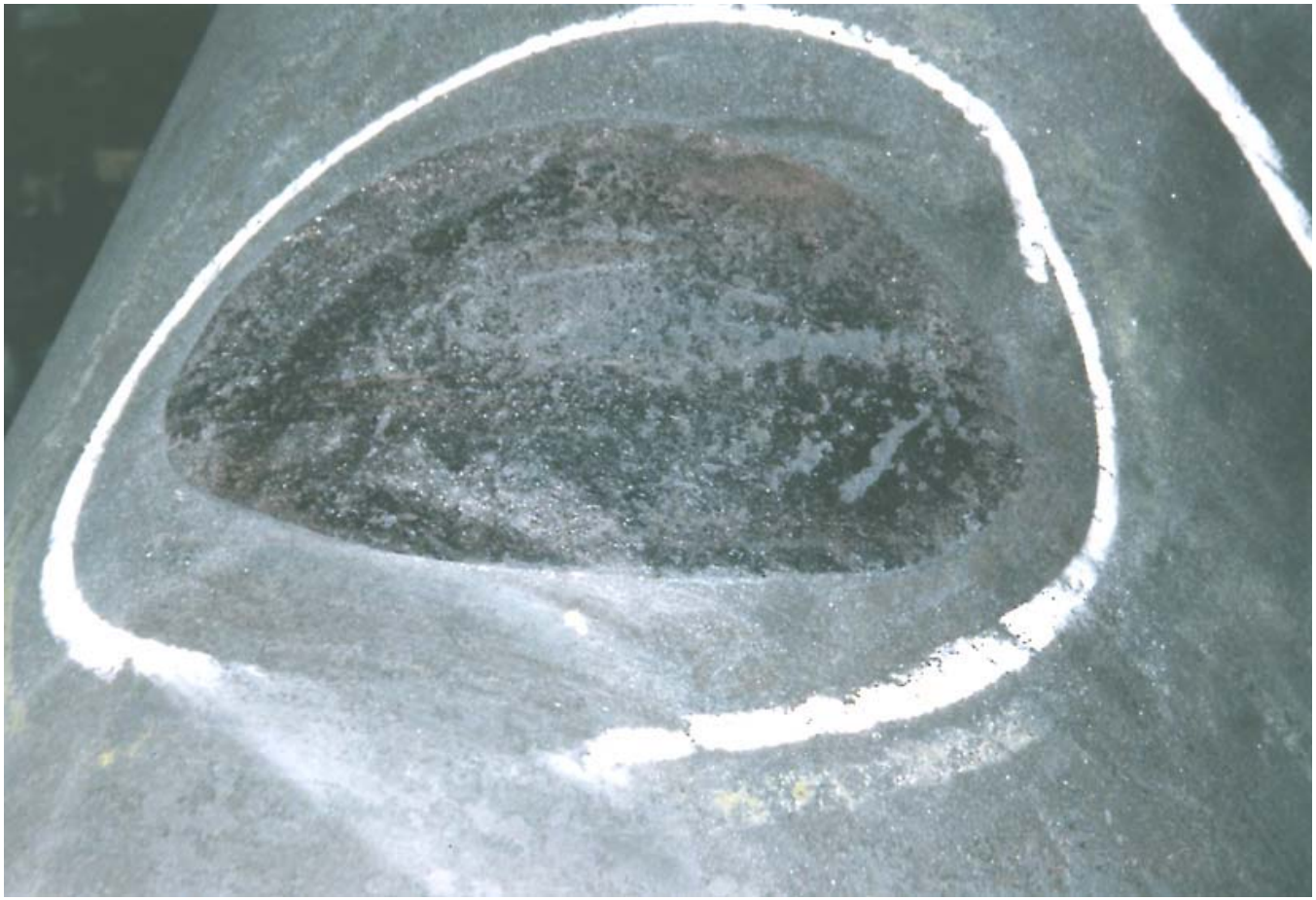


A Major Application of Cast IC-221M is for Heat-Treating Furnace Rolls

General Appearance of Conventional Rolls Inside 160-in. Heat-Treating Furnace at Burns Harbor



Detail of Blister Formed during Service of Stainless Steel Roll Body



Blisters Must be Removed by Hand Grinding to Prevent Scoring of Plates

First Lot of Fabricated Rolls of Nickel Aluminide for Installation at Bethlehem Steel

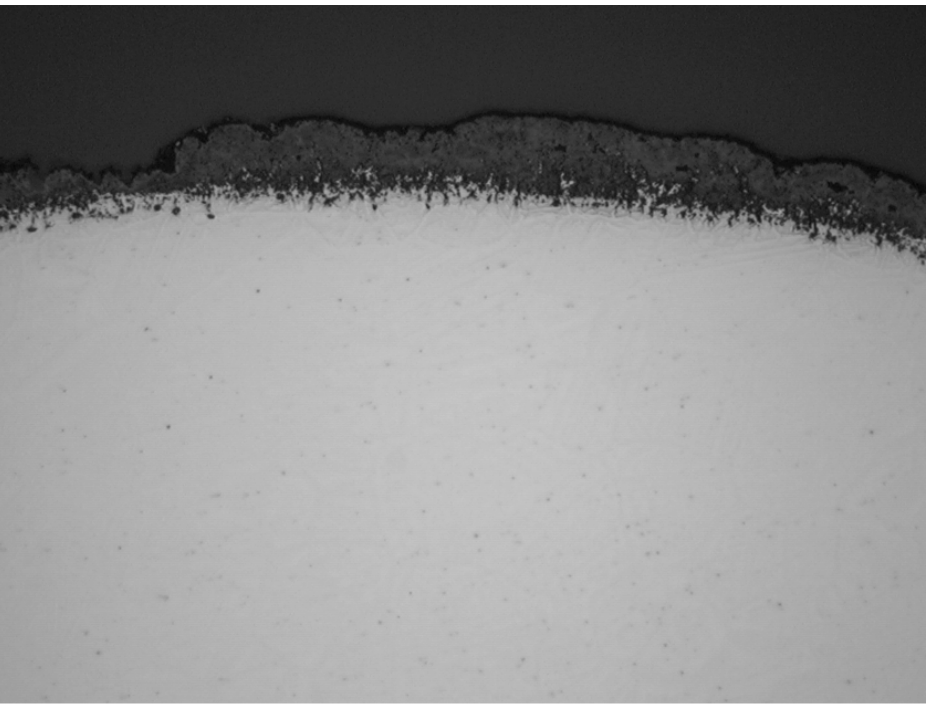
Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

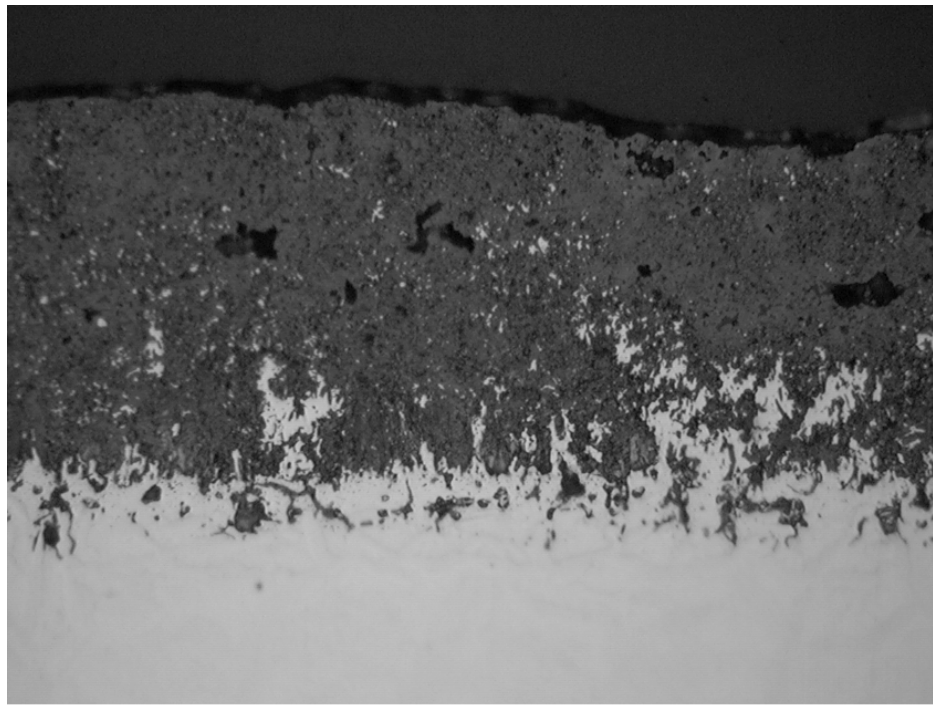
- Intermetallics (Continued)
  - FeAl-based alloys developed in 1990-2002 (limited use)
    - Ordered alloy ductilized with controlled additions of Mo, Zr, and B
    - Excellent resistance to
      - Oxidation
      - Carburization and coking
      - Molten salts
    - Castable with limited ductility
    - Processable into sheet through powder metallurgy
    - Useable as coatings or bimetallic

Examples of High Temperature Metallic and Intermetallic Materials Developed or Under Development at ORNL (Continued)

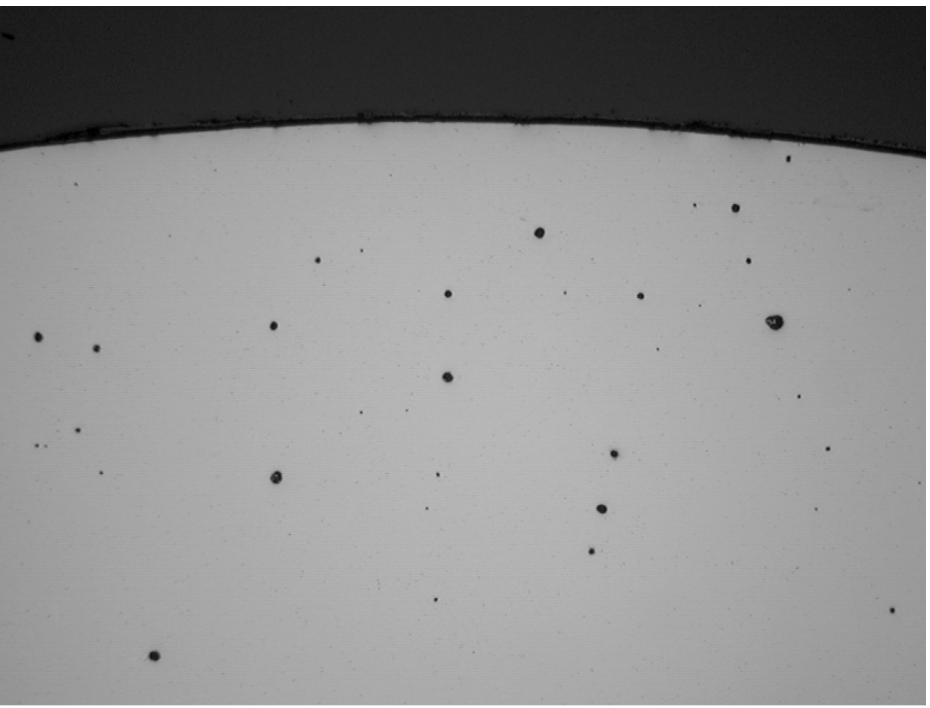
- Intermetallics (Continued)
  - FeAl-based (Continued)
    - Good creep strength up to 800°C
    - Major applications include
      - Microheating elements
      - Hot gas clean-up filters
      - Ethylene tubes as bimetallics
    - Producers with experience include
      - Ametek
      - Duraloy Technologies

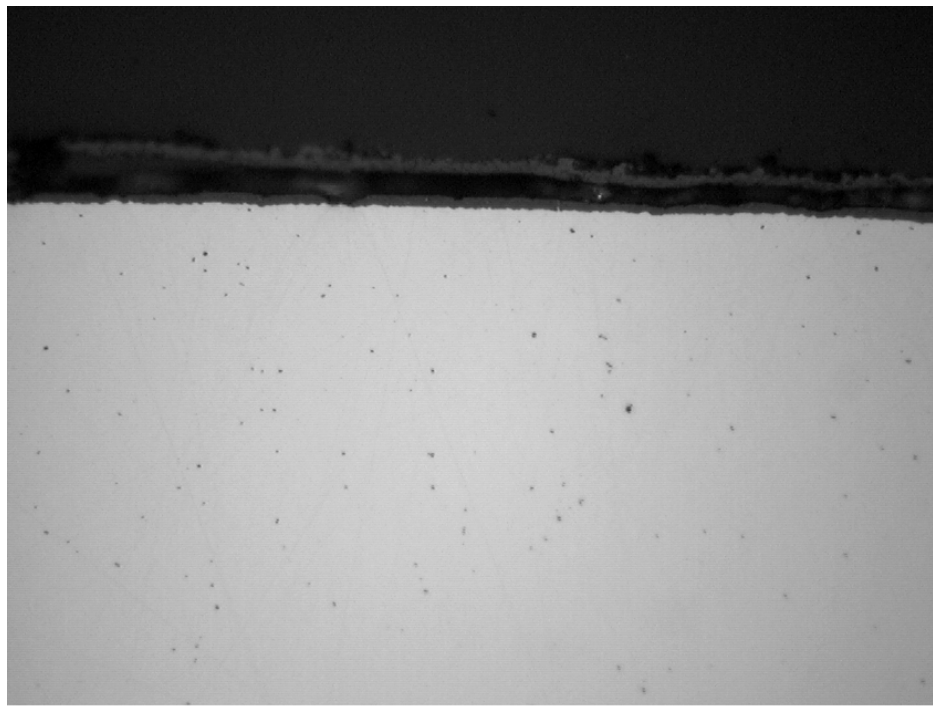
Alloy 803 Showed Extensive Coking and Carburization at 1100°C in 120 Hours





Iron Aluminide (Powder Consolidated) Showed Minimal Reaction in Coking Environment at 1100°C in 138 Hours





Summary

- High Temperature Materials are a Challenge for Improving Efficiency of Many of the Manufacturing Processes.
- Only Limited Effort is Under Way in the U.S. for New Developments of High Temperature Materials.
- ORNL-Developed Grade 91 and Intermetallics have Benefited Some of the Major Applications.
- Exciting Work is Under Way on the Development of Fe-3Cr-3W(v) Steels and the Enhancement of H-Series Stainless Steels.
- Development of Nanophase-Strengthened Materials Offers a New Opportunity for the Next Generation of High Temperature Materials.